



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Variations in seed and post-harvest residue yields and residues quality of common bean (*Phaseolus vulgaris* L.) as a ruminant feedstuff

Citation for published version:

Dejene, M, Dixon, RM, Duncan, AJ, Wolde-meskel, E, Walsh, KB & Mcneill, D 2018, 'Variations in seed and post-harvest residue yields and residues quality of common bean (*Phaseolus vulgaris* L.) as a ruminant feedstuff', *Animal Feed Science and Technology*, vol. 244, pp. 42-55.
<https://doi.org/10.1016/j.anifeedsci.2018.07.017>

Digital Object Identifier (DOI):

[10.1016/j.anifeedsci.2018.07.017](https://doi.org/10.1016/j.anifeedsci.2018.07.017)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Animal Feed Science and Technology

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



1 **Variations in seed and post-harvest residue yields and residues quality of common**
2 **bean (*Phaseolus vulgaris* L.) as a ruminant feedstuff**

3
4 Mesfin Dejene^{a 1}, Rob M. Dixon^b, Alan J. Duncan^c, Endalkachew Wolde-meskel^c, Kerry B.
5 Walsh^d, David McNeill^e

6
7 ^a *Queensland Alliance for Agriculture and Food Innovation (QAAFI), The University of*
8 *Queensland, Gatton, Qld, 4343, Australia*

9 ^b *QAAFI, The University of Queensland, 25 Yeppoon Road, PO Box 6014, Red Hill,*
10 *Rockhampton, Qld 4701, Australia*

11 ^c *International Livestock Research Institute (ILRI), PO Box 5689, Addis Ababa, Ethiopia*

12 ^d *Central Queensland University, Rockhampton, 4701, Australia*

13 ^e *School of Veterinary Science, The University of Queensland, Gatton, Qld, 4343, Australia*

14 **ABSTRACT**

15 Common bean is widely grown as a food legume and the post-harvest crop residues (CR)
16 (i.e. haulm + pod wall (HPW)) are valuable as ruminant feedstuffs. The yields and
17 constituents indicative of nutritive value for ruminants of the HPW from a wide range of
18 common bean genotypes (G) were examined at 4 trial sites in Ethiopia during the 2013
19 main cropping season to assess the extent of genetic variation among G for simultaneous
20 improvement of both HPW attributes and seed yield. Attributes measured were seed and
21 HPW yields and the amounts of the morphological components, their concentrations of
22 total nitrogen (N), neutral detergent fibre (aNDFom) and acid detergent fibre (ADFom), and
23 the dry matter digestibility (DMD). The constituents were measured using near infrared

¹ *Present address:* Ethiopian Institute of Agricultural Research (EIAR), Holetta Research Centre, PO Box 2003, Addis
Ababa, Ethiopia. *E-mail addresses:* mesfindegene@yahoo.co.uk, mesfin.ejigu@uq.net.au

spectroscopy (NIRS) and calibrations based on a large set of reference tropical forages and CR (including common bean), and were validated against other CR reference samples. These CR quality attributes were very well predicted with R^2v and $RPDv$ ranging from 0.90 to 0.98 and 3.13-7.36, respectively. There was considerable variation in yields of HPW and seed, and in the proportions and attributes of the HPW fractions among the common bean G. Trial site means for yields of HPW and seed ranged from 0.74-2.54 t/ha and 0.79 - 2.62 t/ha, respectively while for N, aNDFom and ADFom concentrations and DMD of HPW ranged from 7.7-11.4 g/kg DM, 648-739 g/kg DM, 502-585 g/kg DM, and 467-570 g/kg DM, respectively. Environment (E), as represented by site, generally affected the yields of HPW and seed ($P<0.001$) and nutritive value of the HPW fractions ($P<0.05$) as feedstuffs. Seed yield was positively correlated with HPW yield both within and across trial sites ($r=0.92$; $P<0.0001$), but in general seed yield was not related to the N concentration. Across all sites, seed yield was positively correlated ($r=0.68$; $P<0.0001$) with haulm DMD. Although this correlation may be due to variation associated with E rather than G, it is nevertheless important in that selection for higher seed yield is likely to also increase metabolisable energy (ME) content of the HPW. There were G x E interaction effects on yields of HPW ($P<0.0001$) and seed ($P=0.011$), but these were generally less important than E effects which explained 52-58% of the variation. In conclusion the study demonstrated that it is possible to identify genotypes such as ECAB0081 which combine high yields of both seed and HPW, and with HPW attributes which improve their quality as ruminant feedstuffs.

45

46 **Keywords:** Common bean, Grain legumes, Haulm, Ruminants, East Africa

47

48 **Abbreviations:** ADFom, Acid detergent fibre corrected for the ash concentration of the residue; aNDFom, Neutral
49 detergent fibre assayed with α -amylase and corrected for the ash concentration of the residue; CR, crop residues; CV,
50 Coefficient of variation; DDM, Digestible dry matter; DM, Dry matter; DMD, dry matter digestibility; E, environment; G,

51 genotypes; HI, Harvest index; HPW, Haulm + pod wall (whole CR); IVOMD, In-vitro organic matter digestibility; LSD,
52 Least significant difference ($P=0.05$); ME, Metabolisable energy; N, Concentrations of total nitrogen; NA, North
53 Australian; NIRS, Near infrared spectroscopy; R^2 , The coefficient of determination in calibration; R^2_v , the coefficient of
54 determination in validation values; RPDv, the relative predictive determinant = standard deviation of validation data set/
55 SEP(C); PUI, Potential utility index; SECV, Standard error of cross validation; SEP, Standard error of performance;
56 SEP(C), the SEP corrected for bias.

57

58 **1. Introduction**

59

60 *Phaseolus vulgaris* L., often known as bean, common bean, haricot bean, kidney bean
61 or field beans is a very important grain legume crop in eastern and southern Africa (Beebe
62 et al., 2011), and also globally. Since common bean is usually consumed as the mature
63 seed, the primary objective of genetic improvement programs is usually increasing seed
64 yield. The amount and quality of post-harvest residues from common bean crops, although
65 important in many smallholder crop-livestock systems as ruminant feedstuffs (Asfaw and
66 Blair, 2014), are rarely considered (Beebe et al., 2013; Blümmel et al., 2012; Mekbib,
67 2002; Tullu et al., 2001). Crop residues (CR) from common bean crops are, as for other
68 grain legume CR, usually retained after harvest and used as livestock feedstuffs during the
69 dry season, and usually for ruminants (Yoseph et al., 2014). They are particularly
70 important due to their generally higher N and metabolisable energy (ME) concentrations
71 than cereal CR (Capper, 1990; López et al., 2005; Mekbib, 1997). Although use of
72 common bean CR (haulm + pod wall (HPW)) during the dry season as ruminant feedstuffs
73 is routine in crop-livestock systems, little quantitative information is available on their
74 nutritive value compared to that for cereal CR (Capper, 1990; Nigam and Blummel, 2010).
75 Objective information on the feeding value of common bean HPW is limited to a few
76 reports involving goats (Ayoade et al., 1983; Pieltain et al., 1996) and cattle (Aredo and
77 Musimba, 2003; Ebro et al., 2005). However, each of these studies was limited to a single

78 batch of HPW and usually without description of the genotype, environment, or the
79 morphological components.

80

81 Exploiting plant genetic variability and selection of more appropriate dual-purpose crop
82 genotypes that combine good food grain yields with high yield and quality of the CR as
83 feedstuffs (Blümmel et al., 2013; Lenné et al., 2003; Sharma et al., 2010) are likely to be
84 particularly appropriate for smallholder farmers.(De Groote et al., 2013). There appears to
85 be considerable potential for selecting improved genotypes of the CR of maize (Blümmel
86 et al., 2013; Lenné and Thomas, 2006), sorghum and pearl millet (Blümmel et al., 2003;
87 Sharma et al., 2010) and some grain legumes (Kafilzadeh and Maleki, 2012; Nigam and
88 Blummel, 2010; Prasad et al., 2010; Singh et al., 2003) without compromising grain yield.

89

90 The present study was designed to: (1) assess the extent of genetic variation in yields
91 of seed and HPW, and HPW quality attributes, among current popular common bean
92 genotypes (G) in East Africa, (2) examine the main and interaction effects of G and E, (the
93 latter was represented by site) on yields of seed and HPW, and on HPW quality attributes,
94 and (3) investigate the associations among HPW attributes and seed yield to evaluate the
95 consequences of such interrelationship for simultaneous improvement.

96

97 **2. Materials and methods**

98 *2.1. Trial site descriptions*

99 The study was undertaken during the 2013 cropping season at four trial sites in the
100 south (at *Shalla Wereda* (local administrative unit)), West (at *Bako-Tibe Wereda*), South-
101 west (at *Boricha Wereda*) and North-west (at *Mandura Wereda*) regions of Ethiopia. The
102 trial sites and genotypes tested are summarized in Table 1. Sites were selected to
103 represent smallholder crop-livestock systems where common bean is an important grain

104 legume crop (Farrow, 2014). The genotypes were chosen to represent those well-adapted
105 and often grown by smallholder farmers in each of the regions, and for which seed was
106 readily obtainable. Not all genotypes were available at each site except at Boricha and
107 Mandura (Table 1).

108 TABLE 1 NEAR HERE

109

110 *Shalla* site located in the central Rift valley, represented an erratic and unreliable rainfall
111 characterized by a short rainy season from February/March through to April followed by a
112 main rainy season from June through to September, and with the remaining months
113 generally dry (Dinka et al., 2010). The mean annual minimum and maximum temperatures
114 were 14.0°C and 28.7°C, respectively. During the 2012 and 2013 cropping seasons the
115 annual rainfalls were 925 mm and 920 mm, respectively (MARC, 2014).

116

117 *Bako-Tibe* site was characterized by bimodal rainfall, with a short rainy season
118 beginning in March and continuing intermittently until the main rainy season from June to
119 October (Hassen et al., 2006). The minimum, maximum and mean monthly temperatures
120 recorded during the 2013 cropping season were 12.9, 29.1 and 21.0°C respectively.
121 During the 2012 and 2013 cropping seasons the area received annual rainfall of 887 mm
122 and 1431 mm, respectively (Abebe and Feyisa, 2017).

123

124 *Boricha* site was characterized by a bimodal rainfall pattern, with a short rainy season
125 from February/March to April and a main rainy season from June/July to October (Asfaw et
126 al., 2013). Annual temperature varies from 20–33°C (Quinlan et al., 2015).

127

128 The minimum, maximum, and annual mean temperatures at *Mandura* site were 16.8,
129 27.4 and 24.5°C respectively (Emiru, 2014).

130 2.2. *Experimental design, field data collection and sampling*

131 At each trial site common bean genotypes were examined in a randomized complete-
132 block design with three replicates. The plot size was 3 x 4 m with 8 rows of plants (40 cm
133 between rows and 10 cm between plants within rows). Seeds were hand planted from the
134 27 June to the 24 August 2013 during the main rainy season (Table 1). Fertilizer urea
135 (46.0% w/w N, 4.5 kg N/ha), phosphorus pentoxide (43.6% w/w P, 11.5 kg P/ha) and
136 inoculant (HB-429) were applied. This rhizobium strain had been developed nationally
137 (National Soil Testing Centre, Addis Ababa, Ethiopia) and was that recommended and
138 commonly used by farmers in the area for common bean. Additional information about the
139 sites is available at a project website (N2Africa, 2014). At all sites the crop during the
140 previous season had been common bean.

141

142 At seed maturity plants were harvested from the middle 2m x 2m area of each plot. Two
143 rows were selected for each genotype for total biomass sampling. The number of plants
144 per harvest area was counted, harvested at the soil surface, and then carefully separated
145 avoiding leaf loss into haulms (stems and leaves) and pods. The pods were then
146 separated into the seed and pod wall. The haulm was separated to determine the
147 proportions of leaf and stem components. Following measurement of fresh weight the leaf,
148 stem, pod wall and seed samples were placed into cotton bags, sun-dried and later oven-
149 dried (60°C for 48 h) to determine dry matter (DM). The remaining plants in each plot were
150 harvested to determine seed yield. The yields of HPW fractions, seed and total biomass
151 per unit area were calculated and the seed and HPW yields are reported on a dry weight
152 basis. Harvest index (HI) was calculated as the ratio of seed DM yield to total above
153 ground biomass DM yield at harvest. The potential utility index (PUI), a measure that
154 integrates seed yield with HPW digestible DM (DDM) yield, was calculated (Fleischer et
155 al., 1989) as:

$$\text{PUI} = \frac{\text{Seed DM yield} + \text{DDM HPW yield}}{\text{Total above ground biomass DM yield}}$$

157

158 *2.3. Haulm and pod wall quality analyses*

159 *2.3.1. Haulm and pod wall sample processing*

160 The leaf and stem fractions were recombined to provide haulm. Haulm and pod wall
 161 samples were ground through a 1 mm screen using laboratory hammer mill (Christy and
 162 Norris Limited, Chelmsford, UK) and stored at ambient temperature. Forage samples were
 163 air-freighted to Australia and to meet quarantine requirements were gamma irradiated (25k
 164 Gray) before transport to laboratories in Central Queensland University (CQU) and The
 165 University of Queensland.

166

167 *2.3.2. Measurement of near infrared spectroscopy (NIRS) spectra*

168 All forage samples were scanned using a Foss 6500 monochromator (Silver Springs,
 169 Maryland, USA) fitted with a spinning cup module. This instrument measured spectra at 2
 170 nm intervals over the range 400 – 2500nm. Duplicate subsamples (~ 3 g air-dry) were
 171 packed into the spinning cup cells and scanned as described by Coates and Dixon (2011).
 172 Spectral data were collected with ISI-Scan (Infrasoft International version 4.6.11) software.
 173 Full diagnostic tests on the Foss 6500 NIR Systems monochromator were performed daily
 174 and in addition, the stability of the instrument was monitored by scanning a laboratory
 175 standard sample [Buffel grass (*Cenchrus ciliaris*)] 1-4 times daily.

176

177 Chemometric analyses were conducted with WinISI software version 1.5 and the
 178 spectral data were examined to relate infrared spectra to reference values (Shenk and
 179 Westerhaus, 1991a). Since the samples of the present study were scanned on a different
 180 instrument (the CQU instrument) of the same model to that used to develop the original
 181 North Australian (NA) forage calibration data set (CSIRO instrument), the former spectra

182 were corrected for differences between the instruments. A set of ten sealed standards
183 were scanned a number of times with each monochromator and the ISI software
184 'Instrument Standardisation' procedure used to correct the differences. The CSIRO
185 instrument was considered as the 'primary' instrument and the CQU instrument as the
186 'secondary' instrument.

187

188 2.3.3. Prediction of sample constituents from the NIRS spectra and NIRS calibration

189 Calibrations were developed in two stages. First, the concentrations of total N, neutral
190 detergent fibre (NDF) and acid detergent fibre (ADF), and dry matter digestibility (DMD), in
191 the forages were predicted using the established in-house northern Australian (NA) forage
192 calibrations which had been developed for grasses and legumes in the tropical northern
193 Australian rangelands (NA calibration: D. B. Coates and R. M. Dixon, unpublished results).
194 Most of the samples ($n = 409 - 1688$ depending on the attribute) were C_4 native and
195 naturalized grasses such as the genera *Heteropogon*, *Chrysopogon*, *Urochloa*, *Astrebla*,
196 *Bothriochloa*, *Dichanthium*, *Cynodon*, *Brachiaria*, *Aristida* spp., and the introduced grasses
197 *Cenchrus*, *Chloris*, *Panicum* spp. There were also legumes comprising *Stylosanthes*
198 *scabra* and *S. hamata* and other common introduced tropical and temperate legumes. In a
199 second stage these NA forage calibrations were expanded with additional reference
200 samples comprising a subset of the CR samples (representing species, various
201 morphological fractions, genotypes, year, sites and grain legume crop growth stages at
202 harvest) derived from the present and similar experiments with CR of grain legumes and
203 maize stover from Ethiopia. These additional reference samples were identified on the
204 basis of high standardized global H values (Mahalanobis distance) $^{2/f}$, where f is the
205 number of factors in the model (Shenk and Westerhaus, 1991b) with stratification so that
206 each of the morphological fractions of maize and grain legume species, genotypes, year,
207 sites and grain legume crop growth stages at harvest was represented. Of the CR samples

208 from Ethiopia (maize 1306, common bean 652, chickpea 482, faba bean 351 and soybean
209 60) a subset of 470 samples (maize n=203; common bean n=97, chickpea n=80, faba
210 bean n=65 and soybean n=25; 15-42% of each subclass) were selected as reference
211 samples. These reference samples were analysed for DMD, and concentrations of total N,
212 NDF assayed with α -amylase and corrected for the ash concentration of the residue
213 (aNDFom) and ADF corrected for the ash concentration of the residue (ADFom), by
214 conventional wet chemistry laboratory procedures as described below. These reference
215 samples were then included with the calibration data from NA and the combined data used
216 to calculate and validate improved calibration equations.

217

218 The calibration for each attribute was developed from the reference samples and the
219 NIR spectra using modified partial least squares (Shenk and Westerhaus, 1991b) and
220 WinISI II (version 1.5) software (Infrasoft International, Port Matilda, PA, USA). Critical 'T'
221 and 'H' outlier values were set at 4 and 10, respectively; and where these critical values
222 were exceeded the sample was eliminated as an outlier. Spectra with standardized global
223 H values > 3.0 were also removed as spectral outliers. Calibration development used two
224 outlier elimination passes, a maximum of 16 terms and four cross-validation groups with
225 principal component analysis and 2,4,4,1 math treatment over the 1100-2500 nm
226 wavelength band. The revised calibrations were then used to predict the attributes in the
227 common bean CR samples for the present experiment.

228

229 2.3.4. NIRS validation

230 The robustness of the calibrations was evaluated using established validation
231 procedures. The samples within each species of CR from Ethiopia were randomly divided
232 into two subsets A and B. The NA data were combined with the A and B subsets data (i.e.
233 data set NA+A and NA+B) to develop calibration equations. These were then validated by

234 examining the errors associated with the prediction of the B and A data sets, respectively
235 in terms of the standard error of performance (SEP), the SEP corrected for bias [SEP(C)]
236 and the coefficient of determination in validation values (R^2_v). The relative predictive
237 determinant (RPD_v = Standard deviation of validation set data/ SEP(C)) was also
238 calculated (Williams, 2001). In the current study, R^2_v and RPD_v were used to classify the
239 performance of a given NIRS equation according to Williams (2001). Since the RPD_v was
240 greater than 3 the NIRS equation was considered to be successful for the present
241 analytical purposes as for most NIRS applications for agricultural products (Williams,
242 2001).

243

244 2.3.5. Wet chemistry analysis of selected reference samples for NIRS

245 Wet chemistry of the CR samples from Ethiopia was conducted to generate reference
246 samples to expand NA forage calibrations and then develop new calibrations for each
247 attribute which were then used to predict the attributes in the common bean CR samples
248 for the present experiment. The lab analyses were done in duplicate. Total N (0.15-0.18 g
249 samples) was determined using a LECO combustion system (TruMac® CN analyser 2013
250 version1.3x) (LECO Corporation, St. Joseph, MI, USA) which complies with AOAC (2005)
251 analysis #990.03. aNDFom concentration was analysed using heat stable α -amylase and
252 sodium sulphite followed by incineration of the fibre residue to correct for ash (aNDFom)
253 (Mertens, 2002; Mertens, 2011). ADFom concentration was determined according to Van
254 Soest et al. (1991). Both the aNDFom and ADFom were analysed using anANKOM²⁰⁰
255 Fibre Analyser (Model200, ANKOM Technology, Macedon, NY, USA) with F57 filter bags
256 (ANKOM 57 micron pore size-ANKOM Technology, NY). In-vitro DMD was determined
257 with the filter bag method in DAISY^{II} incubator (ANKOM Technology, Macedon, Fairport,
258 NY, USA). A laboratory standard sample (*Astrella* spp C₄ grass) and empty blank bags
259 were included in each batch. Laboratory errors in the current study were controlled at an

260 acceptable level, with a coefficient of variation between duplicate analyses of less than
261 5%.

262

263 2.4. Statistical analysis

264

265 Analysis of variance was undertaken using the General Linear Model procedure in
266 Statistical Analysis System (SAS, 2009) software. The model $Y_{ij} = \mu + t_i + e_{ij}$ was used for
267 each of the trial site, where Y_{ij} represents the j^{th} observation ($j = 1, 2, \dots, n_i$) on the i^{th}
268 genotype ($i = 1, 2, \dots, k$). μ represents overall mean effect, t_i represents the i^{th} genotype
269 effect and e_{ij} represents the random error present in the j^{th} observation on the i^{th} genotype.

270

271 The data were not analysed across trial sites *Shalla* and *Bako-Tibe*, or across all sites,
272 due to the differences in the genotypes tested at *Shalla*, *Bako-Tibe* and *Boricha*. However,
273 because the same genotypes were used at *Boricha* and *Mandura* the model $Y_{ij} = \mu + \alpha_i +$
274 $\beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij}$ was used to analyse site (i.e. environment (E)) effects across these two sites,
275 where Y_{ij} was the mean of genotype (G) i in environment j , μ was the overall mean, α_i and
276 β_j were the main genotype and environment effects, $(\alpha\beta)_{ij}$ was the G x E interaction effect,
277 and ε_{ij} was the residual associated with genotype i in environment j . Linear relationships
278 between yield, composition and residue digestibility were analysed by SAS Proc Corr. The
279 comparison of means between genotypes and environments was carried out using the
280 least significant difference (LSD) test where the F-tests indicated significant difference
281 ($P < 0.05$).

282 3. Results

283 3.1. *Development of the modified NIRS calibrations and the expected errors in the NIRS* 284 *measurement of attributes of the samples*

285 The frequent measurements (n = 91) of the laboratory standard indicated stability of the
286 instrument with coefficients of variation of 0.687, 0.290, 0.323 and 0.449% for total N
287 concentration, DMD, aNDFom and ADFom, respectively. There was a wide range in the
288 reference values for each of the constituents (n=2068, range 2.2-54.5 g/kg DM for N;
289 n=1320, range 253-891 g/kg DM for DMD; n= 877, range 222-886 g/kg DM for aNDF and
290 n= 855, range 181-704 g/kg DM for ADFom) in both the NA and the Ethiopian CR data
291 sets. The coefficients of determination in calibration (R^2) of known forage quality values on
292 NIRS values were ≥ 0.93 for the four constituents, with that for total N being highest at
293 0.98. Inclusion of the Ethiopian CR data set into the NA forage data set resulted in
294 improvement in calibration R^2 values for DMD (0.88 vs 0.93). The SECV was reduced
295 slightly for each attribute but there were no changes in the R^2 values for total N and the
296 fibre fractions.

297

298 The validation statistics of the NIRS calibration (NA +A) from predicting half of the
299 common bean CR samples (validation set B) showed that N (n=48) and aNDFom (n=49)
300 concentrations and DMD (n=46) were successfully predicted by NIRS with $R^2_v > 0.90$
301 (range 0.91-0.97) and $RPD_v > 3$ (range 3.07-5.06). The ADFom (n=49) concentration was
302 predicted less successfully, with $R^2_v = 0.76$ and $RPD_v = 2.02$. The validation statistics of
303 the NIRS calibration (NA +B) from predicting half of the common bean CR samples
304 (validation set A) showed that N (n=49), aNDFom (n=48) and ADFom (n=48)
305 concentrations were successfully predicted with $R^2_v > 0.91$ (range 0.92-0.99) and RPD_v
306 > 2.9 (range 2.95-8.57). However, HPW DMD was not well predicted ($R^2_v = 0.44$ and
307 $RPD_v = 1.19$). The final calibration used, which was calculated from the NA+A+B data set,

would be expected to further improve R^2v and RPDv values and reduce the prediction error as SEP or SEP(C). The R^2v and RPDv for prediction of common bean HPW (n=97) from the NA+A+B calibration in the present experiment were ≥ 0.90 and >3 , respectively. Also the SEP was less than 45.2 g/kg for DMD, and less than 1.6, 41.6 and 33.4 g/kg for the total N, aNDFom and ADFom concentration, respectively. Generally common bean HPW (n=97) quality attributes as total N, DMD, aNDFom and ADFom were very well predicted by NIRS using the NA+A+B with R^2v and RPDv ranging from 0.90 to 0.98 and 3.13-7.36, respectively.

316

3.2. Variations in seed and post-harvest residue yields and residue yield components among common bean genotypes

3.2.1. Seed and post-harvest residue yields and harvest index

Seed yield varied among genotypes at *Shalla* and *Mandura* ($P < 0.001$), but not at sites *Bako-Tibe* and *Boricha* ($P > 0.05$) (Tables 2 and 3). Similarly, HPW yield and HI generally varied among genotypes, the exceptions being at *Bako-Tibe* for HPW and at *Boricha* for HI. There were genotype differences ($P < 0.01$) in PUI only at *Shalla*. The highest seed (3.47 t/ha) and HPW (3.36 t/ha) yields were observed for genotypes Nasir and ECAB0081 at *Shalla*, and the lowest for Argene and Loko were 0.46 t/ha for seed at *Mandura* and 0.52 t/ha for HPW at *Bako-Tibe* (Tables 2 and 3).

327

There were wide ranges across all sites in yields of seed (mean 1.42, range 2.05 - 3.47 t/ha) and HPW (mean 1.77, range 1.59-3.36 t/ha), and in HI (mean 0.51, range 0.47-0.56), and the greatest ranges were observed at *Shalla*. Genotype ECAB0081 at *Shalla* gave the highest seed and HPW yields but did not consistently provide higher HI (Table 2). Similarly higher yielding genotypes at *Mandura* did not consistently provide higher HI (Table 3). The lowest yielding genotype Awash-1 at *Shalla* and *Mandura* (Tables 2 and 3) also tended to

334 have a higher HI. When data were combined across *Boricha* and *Mandura* (Table 3) the
335 differences among genotypes were substantial ($P < 0.05$ and $P < 0.001$) for seed and HPW
336 yields. Also site (i.e. E) affected yields of seed ($P = 0.0007$) and HPW ($P < 0.001$). Genotype
337 x E also affected yields of seed ($P = 0.011$) and HPW ($P < 0.0001$). In general, the variation
338 observed among genotypes at each trial site was higher for HPW yield than seed yield.

339
340 TABLE 2 NEAR HERE

341 TABLE 3 NEAR HERE
342

343 *3.2.2. Leaf, stem and pod wall fractions*

344 The stem fraction always constituted the highest proportion of HPW at harvest (means
345 ranging from 633-692 g/kg DM) followed by pod wall (256-299 g/kg DM). Leaf comprised
346 only 52-69 g/kg DM in HPW and was ≤ 87 g/kg DM (Tables 2 and 3). The proportion of
347 pod wall to seed in the whole pods ranged from 191-267 g/kg DM (values not shown).
348 There were generally large differences ($P < 0.01$) amongst genotypes in the proportions of
349 leaf, stem and pod wall fractions in the HPW (Tables 2 and 3), and in leaf to stem ratio
350 ($P < 0.0001$) (values not shown). When data were combined across *Boricha* and *Mandura*
351 (Table 3) the leaf and stem proportions were affected by genotype ($P < 0.0001$; $P = 0.035$),
352 and tended to differ for pod wall proportion ($P = 0.061$). Environment had no effect ($P > 0.35$)
353 on the proportion of any of the morphological fractions but there was a G X E interaction
354 for the proportions of leaf ($P < 0.0001$) and stem ($P = 0.04$).

355 *3.3. Variations in quality attributes of post-harvest residue fractions and HPW among*
356 *common bean genotypes*

357 Trial site means for concentrations of N, aNDFom and ADFom and for DMD in HPW
358 ranged from 7.7-11.4 g/kg DM, 648-739 g/kg DM, 502-585 g/kg DM, and 467-570 g/kg

DM, respectively (Tables 4 and 5). There were also wide differences ($P<0.01$) amongst the HPW and the pod wall and haulm fractions of the genotypes for each of the laboratory nutritive quality attributes measured at *Shalla* and *Bako-Tibe* (Table 4). For instance at *Shalla* the mean total N concentration in HPW varied two-fold (range 6.1-12.5 g/kg DM, mean 9.6 g/kg DM). At sites *Bako-Tibe* and *Mandura* the mean total N concentration in HPW varied from 8.6-13.2 g/kg DM and from 6.4-11.1 g/kg DM, with mean values of 11.4 g/kg DM and 8.5 g/kg DM, respectively (Tables 4 and 5). Similarly, large variations (range 139 and 132 g/kg DM units) in DMD were observed at *Shalla* and *Bako-Tibe*, respectively (Table 4). In general HPW quality attributes for genotype ECAB0081 (e.g. HPW DMD 647 g/kg DM and total N 12.5 g/kg DM) were higher than for other genotypes at *Shalla* (Table 4). This genotype also had higher PUI than the other genotypes (Table 2).

370

371

TABLE 4 NEAR HERE

372

TABLE 5 NEAR HERE

373

When data were combined across *Boricha* and *Mandura* (Table 5), site affected the DMD ($P=0.020$), and concentrations of N ($P=0.017$), aNDFom and ADFom ($P<0.001$) in HPW. Similarly E had significant effects on all fodder quality parameters measured for the HPW fractions but did not affect N concentration or DMD of the pod wall fraction. The G x E interaction was significant ($P<0.05$) for all quality parameters measured for the pod wall fraction but not for the haulm or the HPW.

3.4. Relationships between seed and HPW yields, and total biomass yield

Across all trial sites there was a positive relationship between the yields of HPW and seed both within each site and for data pooled across sites ($r=0.92$; $P<0.0001$; $n=33$) (Figure 1). Thus there was also a strong association ($r=0.98$; $P<0.0001$; $n=33$) between

384 seed yield and total biomass yield across sites (values not shown). However there was no
385 general association between seed yield and HI.

386

387 FIGURE 1 NEAR HERE

388

389 3.5. Relationships between seed yield and HPW quality attributes

390 There were no relationships ($P>0.05$) between seed yield and HPW DMD at any of the
391 trial sites considered independently, but there was a positive association ($r= 0.68$;
392 $P<0.0001$; $n=33$) in the pooled data between seed yield and HPW DMD (Figure 2). In the
393 pooled data there was no association ($r= -0.22$; $P=0.22$; $n=33$) between seed yield and
394 HPW N concentration (Figure 3), although this relationship was significant at *Mandura* ($r= -$
395 0.90 ; $P<0.001$; $n=9$).

396

397 FIGURE 2 NEAR HERE

398 FIGURE 3 NEAR HERE

399

400 4. Discussion

401 4.1. Variations in seed and post-harvest residue yields and residue yield components 402 among common bean genotypes

403 The large genetic variation among common bean genotypes in yields of seed and HPW
404 in the present study, particularly at Shalla and *Mandura*, were comparable with the large
405 variation in seed yield often reported (Araújo and Teixeira, 2003; Tadesse et al., 2014).
406 Furthermore in the present study the variation among genotypes was generally higher for
407 HPW yield than for seed yield. The positive relationship between yields of seed and haulm
408 (Figure 1) indicated that selection of genotypes for high seed yield will on average

409 increase haulm yield almost proportionately (by 98%), although there is likely to some
410 variation in HI. Similarly Scully and Wallace (1990) and Erskine et al. (2000) reported that
411 genotypes with higher seed yields had higher haulm yields also indicating that yields of
412 seed and haulm can be increased concurrently. The observation in the present study that
413 haulm DMD generally increased considerably (up to 150 g/kg units of DMD) (Figure 3), is
414 also important since it indicates that selection for increases in seed yield are likely to
415 increase, and is not likely to decrease, the ME content of the CR for ruminants.

416

417 The importance of G and G x E differences varied among the trial sites and therefore E.
418 At *Bako-Tibe* there were no differences in seed or haulm yields due to genotype but this
419 was associated with very low yields (means 0.79 and 0.74 t/ha, respectively) (Table 2)
420 compared with those in the other three environments (mean 1.32-2.62 and 1.61-2.54 t/ha,
421 respectively). This demonstrated the importance of E effects. In addition at *Boricha* and
422 *Mandura* where the G x E interactions could be examined there were interaction effects on
423 the yields of both seed and HPW, and on the morphological proportions of leaf and stem
424 (Table 3). These yields attributes demonstrated G x E interactions were most affected by
425 site or E (52-58%) (values not shown) and did not have a stable yield performance across
426 sites. Other studies have also demonstrated G x E interactions for seed yield in common
427 bean (Gebeyehu and Assefa, 2003; Mekbib, 2002; Mekbib, 2003) also indicating that
428 selection of genotypes for yield of both seed and haulm must also consider the
429 environment.

430

431 4.2. Variations in quality attributes of post-harvest residue fractions and HPW among 432 common bean genotypes

433 As the stem component usually comprised about 630-690 g/kg of the CR the nutritive
434 value of the entire CR was highly dependent on the nutritional quality of the stem. Most of

435 the remaining CR fraction comprised pod wall which was much lower in both aNDFom and
436 ADFom, and higher in DMD (ranging from 616-660 g/kg across sites) than HPW fraction.
437 When the pods are shelled to remove the seed there may be opportunity to collect pod
438 wall and use this CR fraction separately to provide a feedstuff of higher ME concentration.
439 However the pod wall was, like haulm, low in N concentration and would require additional
440 dietary N to provide for even moderate production by ruminants. Leaf is well known to be
441 high in N and digestibility (Pieltain et al., 1996) and to be usually associated with high
442 voluntary intake, but because it comprised only a small proportion of the CR (generally
443 only 50-70 g/kg) had little effect on the nutritive value of the entire CR. The low proportion
444 of leaf in the CR was most likely associated with extensive loss of leaf during the later
445 stages of plant growth and/or at harvest and was an important factor in the low nutritive
446 value of the CR (Asfaw and Blair, 2014; Larbi et al., 1999). Selection of genotypes and
447 modification of harvest procedures (earlier harvesting of CR soon after attaining
448 physiological maturity before the quality deteriorates) to increase the proportion of leaf in
449 the CR is likely to have important effects to increase the nutritional value of the CR. The
450 proportion of leaves in forage declines and this is usually more pronounced in food
451 legumes than cereals (Batterham and Egan, 1986). The differences observed between
452 leaf-rich and stem-rich straws of legumes in general, and common bean in particular,
453 confirm the importance of morphological composition of the legume CR to its nutritive
454 value (López et al., 2005). Moreover, if genotypes that retain their leaf at crop
455 physiological maturity can be identified and this attribute selected effectively, it could be
456 included by plant breeders into genotypes selection criteria with a major impact in
457 increasing the nutritive value of the CR.

458

459 There was substantial variation among genotypes in the present study in N
460 concentration and DMD of the CR with the genotypes ECAB0081, GLP2 and Awash-1 at

461 *Shalla* and genotype H-Dume at *Bako-Tibe* being of higher value (Table 4). These higher
462 values could be partly attributed to the differences in the proportions of the morphological
463 fractions or higher leaf proportion in the HPW (Table 2). Conversely the lower mean DMD
464 of the HPW at *Bako-Tibe* than *Shalla* and *Boricha* might be attributed to the higher stem
465 (692 g/kg) and the lower leaf (52 g/kg) and pod wall (256 g/kg) in the HPW although the
466 relative importance of genotype and environment on these differences could not be
467 identified. These results indicate that there are opportunities to identify genotypes which
468 provide CR of higher value as ruminant feedstuffs in specific environments. However,
469 additional diet N will still be required to provide for the requirements for animal productivity
470 rather than maintenance, especially if the common bean CR are fed mixed with cereal CR
471 of usually even lower N concentration. It is generally accepted that forages need to
472 contain at least 10 g N/kg with a DM digestibility of 500 g/kg DM to provide for
473 maintenance or slow growth of ruminants, while a DMD of 550-600 g/kg DM is needed for
474 moderate growth or for lactating animals (Minson, 1990; Van Soest, 1994). It is clear that
475 the nutritional value as concentrations of N and ME of common bean CR is generally low
476 and when fed alone is suitable only for maintenance or moderate growth of non-lactating
477 animals.

478

479 The few studies available have reported the composition of common bean residues in
480 the range 0.8 – 1.6 g N/kg DM, 510-690 g NDF/kg DM, 373-565 g ADF/kg DM, and DMD
481 of 530-590 g/kg DM (Aredo and Musimba, 2003; Ayoade et al., 1983; Ebro et al., 2005;
482 López et al., 2005). Voluntary intake by cattle and goats has ranged from 18-30 g DM/kg
483 live weight and hence has tended to be higher than usually observed with cereal CR
484 harvested at grain maturity (Capper, 1990). For instance voluntary intake of maize stover
485 by cattle and sheep ranged from 14-19 g DM/kg live weight, respectively (Aredo and
486 Musimba, 2003; Koralagama et al., 2008; Tolera and Sundstøl, 2000). The mean values

487 for the nutritional attributes of common bean CR observed in the present study were
488 generally in accord with these previous reports although both the N concentration and
489 DMD tended to be lower in the present study. Only at *Bako-Tibe* were the concentrations
490 of N, and at *Shalla* the DMD of the HPW, comparable with those reported in the previous
491 studies.

492

493 There is also substantial variation in chemical composition and digestibility of haulms
494 associated with genotype and environment of other grain legume crops such as
495 groundnut, lentil and cowpea genotypes has also been reported (Erskine et al., 1990;
496 Grings et al., 2012; Larbi et al., 1999; Omokanye et al., 2001). For example in a wide
497 range of groundnut cultivars (*Arachis hypogaea*) and breeding lines (n=860), Nigam and
498 Blummel (2010) reported that haulm N content varied almost two-fold (mean=1.7, range
499 12-23 g/kg DM), and IVOMD varied ($P<0.0001$) by almost 100 g/kg DM units (mean 563;
500 range 517-611 g/kg DM). Similarly a wide range has been reported in lentil haulm DMD
501 which varied from 400-490 g/kg DM, and CP content which varied from 58-69 g/kg DM,
502 among cultivars (Erskine et al., 1990).

503

504 4.3. Relationships between seed and HPW yields, and feedstuff quality attributes of post-
505 harvest residue

506 The relationships between seed and biomass yield and quality in food crops are
507 important since crops tend to be bred for seed production even though the biomass is also
508 widely used for livestock feeding in developing countries. Understanding these
509 relationships helps to support the introduction of breeding objectives beyond simply seed
510 yield. The positive relationships between yields of seed and both haulm and total biomass
511 in the present study are comparable with the associations previously reported for common
512 bean (Araújo and Teixeira, 2003; Scully and Wallace, 1990). Although seed yield has also

513 been positively related to HI (Araújo and Teixeira, 2003; Tar'an et al., 2002) it appears that
514 the biomass yield is the most important attribute for yield improvement in common bean
515 (Scully and Wallace, 1990).

516

517 Negative associations between seed yield and HPW N concentration at Mandura may
518 have been due to the translocation of N to seed during crop maturity (Araújo and Teixeira,
519 2003). However the general absence in the present study of strong inverse relationships
520 between total N concentration of haulm with seed yield and the general positive
521 association for DMD indicate that there is opportunity to select for higher seed yield
522 without adverse effects, or with an improvement, in the nutritional value of the HPW as a
523 ruminant feedstuff.

524

525 Fodder related attributes of the CR have not been considered as selection criteria for
526 new varieties of common bean in EA. However, as Schiere et al. (2004) have pointed out it
527 would be valuable for plant breeders to consider higher total biomass yield, at least
528 equivalent HI, and higher leaf to stem ratio and stem quality as selection criteria to improve
529 whole plant value rather than considering only for the value of higher seed yield. Similar
530 arguments have been made in relation to plant breeding for lentil (Kusmenoglu and
531 Muehlbauer, 1998; Tullu et al., 2001) and other grain legumes (Kafilzadeh and Maleki,
532 2012; Nigam and Blummel, 2010; Prasad et al., 2010; Singh et al., 2003). Blümmel et al.
533 (2012) also concluded that in groundnut there are strong opportunities for breeding in
534 parallel for high productivity and high fodder quality even under drought stress.

535

536

537

538 **5. Conclusions**

539

540 The CR of common bean as ruminant feedstuffs are important in many crop-livestock
541 smallholder farming systems but the yield and nutritive value of the CR component are
542 seldom considered during the selection of improved genotypes. The present study showed
543 that there is considerable variability in the yield and nutritive value of the CR among
544 genotypes which are widely grown in East Africa and that selection for these attributes
545 need not compromise seed yield. However collaboration among plant breeders, livestock
546 scientists and farmers is needed to achieve such outcomes.

547 **Conflict of interest**

548

549 The authors have no conflicts of interest to declare.

550

551 **Acknowledgements**

552

553 We greatly appreciate the support from Australian Centre for International Agricultural
554 Research through a John Allwright Fellowship for Mesfin Dejene to study at the University
555 of Queensland. The assistance received through the SIMLESA (*Sustainable Intensification
556 of Maize-Legume cropping systems for food security in Eastern and Southern Africa*)
557 project, CIMMYT and Ethiopian Institute of Agricultural Research, and ILRI-Addis Ababa
558 for research support through N2Africa project is highly appreciated. We would like to thank
559 the N2Africa research team members at ILRI-Addis Ababa, federal and regional research
560 centres who assisted during field data collection. Samples of CR were imported to
561 Australia under Australian Quarantine Permit-IP14007043.

562

563 **References**

564

565 Abebe Z., Feyisa H. (2017) Effects of nitrogen rates and time of application on yield of
566 maize: rainfall variability influenced time of N application. International Journal of
567 Agronomy 2017:1-10. ISSN: 1687-8159. DOI:
568 <https://doi.org/10.1155/2017/1545280>.

569 AOAC. (2005) AOAC Official Method 990.03. Protein (Crude) in animal feed, combustion
570 method, in Official Methods of Analysis of The Association of Official Analytical
571 Chemists (AOAC) International, 18th Edition (2005). Revision 1, 2006, Chapter 4,
572 pp. 30-31 AOAC International, Arlington, VA.

573 Araújo A.P., Teixeira M.G. (2003) Nitrogen and phosphorus harvest indices of common
574 bean cultivars: Implications for yield quantity and quality. Plant and Soil 257:425-
575 433.

576 Aredo T.A., Musimba N. (2003) Study on the chemical composition, intake and digestibility
577 of maize stover, tef straw and haricot bean haulms in Adami Tulu District, Ethiopia.
578 Kasetart Journal 37:401-407.
579 <http://www.thaiscience.info/Journals/Article/TKJN/10898571.pdf>.

580 Asfaw A., Almekinders C.J., Struik P.C., Blair M.W. (2013) Farmers common bean variety
581 and seed management in the face of drought and climate instability in southern
582 Ethiopia. Scientific Research and Essays 8:1022-1037. ISSN 1992-2248.
583 <http://library.wur.nl/WebQuery/wurpubs/fulltext/285770>.

584 Asfaw A., Blair M.W. (2014) Quantification of drought tolerance in Ethiopian common bean
585 varieties. Agricultural Sciences 5:124-139. DOI: 10.4236/as.2014.52016.

586 Ayoade J., Makhambera P., Bodzalekani M. (1983) Evaluation of crop residues as feeds
587 for goats. 1. Voluntary intakes, digestibility and nitrogen utilization of groundnut and

588 bean haulms. South African Journal of Animal Science 13:12-13.

589 <https://www.ajol.info/index.php/sajas/article/view/139466>.

590 Batterham E., Egan A. (1986) Utilization of food legumes as feed, in: E. S. Wallis, Byth,
591 D.E. (Ed.), Food legume improvement for Asian farming systems, ACIAR,
592 Proceedings of an international workshop, Khon Kaen, Thailand 1-5 September
593 1986, ACIAR Proceedings No. 18. pp. 193-200.

594 Beebe S., Rao I., Blair M., Acosta-Gallegos J.A. (2013) Phenotyping common beans for
595 adaptation to drought. Frontiers in Physiology 4:1-20. DOI:
596 doi:10.3389/fphys.2013.00035.

597 Beebe S.E., Rao I.M., Blair M.W., Acosta-Gallegos J.A. (2011) Phenotyping common
598 beans for adaptation to drought, in: P. Monneveux, Ribaut, J.M. (Ed.), Drought
599 Phenotyping in Crops: From Theory to Practice, CGIAR Generation Challenge
600 Programme; International Maize and Wheat Improvement Center (CIMMYT),
601 Texcoco (Mexico). pp. 319-343. ISBN 978-970-648-178-8. 2 v.
602 http://www.generationcp.org/drought_phenotyping.

603 Blümmel M., Grings E.E., Erenstein O. (2013) Potential for dual-purpose maize varieties to
604 meet changing maize demands: synthesis. Field Crops Research 153:107-112.

605 Blümmel M., Ratnakumar P., Vadez V. (2012) Opportunities for exploiting variations in
606 haulm fodder traits of intermittent drought tolerant lines in a reference collection of
607 groundnut (*Arachis hypogaea* L.). Field Crops Research 126:200-206.

608 Blümmel M., Zerbini E., Reddy B., Hash C., Bidinger F., Khan A. (2003) Improving the
609 production and utilization of sorghum and pearl millet as livestock feed: progress
610 towards dual-purpose genotypes. Field Crops Research 84:143-158.

611 Capper B. (1990) The role of food legume straw and stubble in feeding livestock, in: A. E.
612 Osman, Ibrahim, M. H., Jones, M. A. (Ed.), The Role of Legumes in the Farming
613 Systems of the Mediterranean Areas. Developments in Plant and Soil Sciences,

614 Springer, Dordrecht. pp. 151-162. ISBN: 978-94-009-1019-5.

615 https://doi.org/10.1007/978-94-009-1019-5_14.

616 Coates D.B., Dixon R.M. (2011) Developing robust faecal near infrared spectroscopy

617 calibrations to predict diet dry matter digestibility in cattle consuming tropical

618 forages. *Journal of Near Infrared Spectroscopy* 19:507-519.

619 De Groote H., Dema G., Sonda G.B., Gitonga Z.M. (2013) Maize for food and feed in East

620 Africa—The farmers' perspective. *Field Crops Research* 153:22-36.

621 Dinka H., Chala R., Dawo F., Bekana E., Leta S. (2010) Major constraints and health

622 management of village poultry production in rift valley of Oromia, Ethiopia.

623 *American-Eurasian Journal of Agriculture and Environmental Science* 9:529-533.

624 [https://www.idosi.org/aejaes/jaes9\(5\)/12.pdf](https://www.idosi.org/aejaes/jaes9(5)/12.pdf).

625 Ebro A., Tadesse T., Abebe T. (2005) The supplementation of haricot bean residue with

626 lablab (*Lablab purpureus*) hay in the diet of Arsi bulls and heifers (*Bos indicus*).

627 *Tropical Science* 45:114-117.

628 Emiru T.S. (2014) Population dynamics and its impact on land use/cover in Ethiopia: the

629 case of Manduara District of Metekel Zone, Benshangul-Gumuz Regional State,

630 PhD Thesis, University of South Africa, Pretoria. pp. 198.

631 <http://uir.unisa.ac.za/handle/10500/13873>.

632 Erskine W., Kusmenoglu I., Muehlbauer F., Summerfield R. (2000) Breeding for increased

633 biomass and persistent crop residues in cool-season food legumes, in: R. Knight

634 (Ed.), *Linking Research and Marketing Opportunities for Pulses in the 21st Century*.

635 *Current Plant Science and Biotechnology in Agriculture*, Springer, Dordrecht. pp.

636 191-197. ISBN: 978-94-011-4385-1. [https://doi.org/10.1007/978-94-011-4385-](https://doi.org/10.1007/978-94-011-4385-1_17)

637 [1_17](https://doi.org/10.1007/978-94-011-4385-1_17).

638 Erskine W., Rihawi S., Capper B. (1990) Variation in lentil straw quality. *Animal Feed*

639 *Science and Technology* 28:61-69.

640 Farrow A. (2014) Managing factors that affect the adoption of grain legumes in Ethiopia in
 641 the N2Africa project, Wageningen The Netherlands: Wageningen University. pp. 1-
 642 56. <https://cgspace.cgiar.org/handle/10568/70995>.

643 Fleischer J., Barnes A., Awumbila B., Amaning-Kwarteng K., Tieku C. (1989) Grain yield
 644 and nutritive value of crop residues from three varieties of maize (*Zea mays* L) crop,
 645 in: A. N. Said, Dzowela, B.H. (Ed.), Overcoming Constraints to Efficient Utilization of
 646 Agricultural By-Products as Animal Feed. Proceedings of the Fourth Annual
 647 Workshop held at the Institute of Animal Research. African Research Network for
 648 Agricultural By-products (ARNAB), ARNAB, ILCA, Addis Ababa, Ethiopia, Mankon
 649 Station, Bamenda, Cameroun, 20-27 October 1987. pp. 239-255.
 650 <http://www.fao.org/Wairdocs/ILRI/x5490E/x5490e0i.htm>.

651 Gebeyehu S., Assefa H. (2003) Genotype x environment interaction and stability analysis
 652 of seed yield in navy bean genotypes. African Crop Science Journal 11:1-7.

653 Grings E.E., Tarawali S., Blummel M., Musa A., Fatokun C., Hearne S., Boukar O. (2012)
 654 Cowpea in evolving livestock systems, in: O. Boukar, Coulibaly, O., Fatokun, C.A.,
 655 Lopez, K., Tamò, M. (Ed.), Innovative research along the cowpea value chain:
 656 Proceedings of the Fifth World Cowpea Conference on Improving livelihoods in the
 657 cowpea value chain through advancement in science, held in Saly, Senegal, 27
 658 September -1 October 2010, IITA, Ibadan, Nigeria. pp. 322-333.
 659 <https://cgspace.cgiar.org/handle/10568/33516>.

660 Hassen A., Gizachew L., Rethman N. (2006) Effect of *Lablab purpureus* and *Vicia*
 661 *atropurpurea* as an intercrop, or in a crop rotation, on grain and forage yields of
 662 maize in Ethiopia. Tropical Grasslands 40:111-118.
 663 [http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.9063&rep=rep1&type](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.9063&rep=rep1&type=pdf)
 664 [=pdf](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.9063&rep=rep1&type=pdf).

665 Kafilzadeh F., Maleki E. (2012) Chemical composition, in vitro digestibility and gas
 666 production of straws from different varieties and accessions of chickpea. Journal of
 667 Animal Physiology and Animal Nutrition 96:111-118.

668 Koralagama K., Mould F., Fernandez-Rivera S., Hanson J. (2008) The effect of
 669 supplementing maize stover with cowpea (*Vigna unguiculata*) haulms on the intake
 670 and growth performance of Ethiopian sheep. Animal 2:954-691.

671 Kusmenoglu I., Muehlbauer F.J. (1998) Genetic variation for biomass and residue
 672 production in lentil: I. Relation to agronomic traits. Crop Science 38:907-910.

673 Larbi A., Dung D., Olorunju P., Smith J., Tanko R., Muhammad I., Adekunle I. (1999)
 674 Groundnut (*Arachis hypogaea*) for food and fodder in crop-livestock systems:
 675 forage and seed yields, chemical composition and rumen degradation of leaf and
 676 stem fractions of 38 cultivars. Animal Feed Science and Technology 77:33-47.

677 Lenné J., Fernandez-Rivera S., Blümmel M. (2003) Approaches to improve the utilization
 678 of food–feed crops—synthesis. Field Crops Research 84:213-222.

679 Lenné J., Thomas D. (2006) Integrating Crop—Livestock Research and Development in
 680 Sub-Saharan Africa: Option, Imperative or Impossible? Outlook on Agriculture
 681 35:167-175.

682 López S., Davies D.R., Giraldez F.J., Dhanoa M., Dijkstra J., France J. (2005) Assessment
 683 of nutritive value of cereal and legume straws based on chemical composition and
 684 in vitro digestibility. J Sci Food Agric 85:1550-1557.

685 MARC. (2014) Melkassa Agricultural Research Centre
 686 <http://www.eiar.gov.et/index.php/melkassa-agricultural-research-center>.

687 Mekbib F. (1997) Farmer participation in common bean genotype evaluation: the case of
 688 eastern Ethiopia. Experimental Agriculture 33:399-408.

689 Mekbib F. (2002) Simultaneous selection for high yield and stability in common bean
 690 (*Phaseolus vulgaris*) genotypes. The Journal of Agricultural Science 138:249-253.

691 Mekbib F. (2003) Yield stability in common bean (*Phaseolus vulgaris* L.) genotypes.
 692 Euphytica 130:147-153.

693 Mertens D.R. (2002) Gravimetric determination of amylase-treated neutral detergent fiber
 694 in feeds with refluxing in beakers or crucibles: collaborative study. Journal of
 695 Association of Official Agricultural Chemists International 85:1217-1240.

696 Mertens D.R. (2011) What are the five most important things to measure in hay crops?,
 697 Proceedings, 2011 Western Alfalfa and Forage Conference, Mertens Innovation &
 698 Research LLC, Belleville, WI 53508-9727, University of California Coop. Ext.,
 699 University of California, Davis, Las Vegas, NV. 11–13 Dec. 2011.
 700 [http://alfalfa.ucdavis.edu/+symposium/2011/files/talks/11WAS-](http://alfalfa.ucdavis.edu/+symposium/2011/files/talks/11WAS-21_Mertens_HayMeasurements.pdf)
 701 [21_Mertens_HayMeasurements.pdf](http://alfalfa.ucdavis.edu/+symposium/2011/files/talks/11WAS-21_Mertens_HayMeasurements.pdf).

702 Minson D. (1990) Forage in ruminant nutrition Academic Press. ISBN: 9780323147989.
 703 [https://www.elsevier.com/books/forage-in-ruminant-nutrition/minson/978-0-12-](https://www.elsevier.com/books/forage-in-ruminant-nutrition/minson/978-0-12-498310-6)
 704 [498310-6](https://www.elsevier.com/books/forage-in-ruminant-nutrition/minson/978-0-12-498310-6).

705 N2Africa. (2014) Better beans through better agricultural practices for farmers in Ethiopia.
 706 292 N2Africa - Ethiopia common beans booklet.pdf.

707 Negassa W., Gebrekidan H., Friesen D. (2005) Integrated use of farmyard manure and NP
 708 fertilizers for maize on farmers' fields. Journal of Agriculture and Rural Development
 709 in the Tropics and Subtropics (JARTS) 106:131-141.
 710 [http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.888.5702&rep=rep1&type](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.888.5702&rep=rep1&type=pdf)
 711 [=pdf](http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.888.5702&rep=rep1&type=pdf).

712 Nigam S., Blummel M. (2010) Cultivar-dependent variation in food-feed-traits in groundnut
 713 (*Arachis hypogaea* L.). Animal Nutrition and Feed Technology 10S:39-48. ISSN
 714 0974-181X. <http://www.indianjournals.com/ijor.aspx?target=ijo...> .

715 Omokanye A., Onifade O., Olorunju P., Adamu A., Tanko R., Balogun R. (2001) The
 716 evaluation of dual-purpose groundnut (*Arachis hypogaea*) varieties for fodder and
 717 seed production at Shika, Nigeria. *The Journal of Agricultural Science* 136:75-79.

718 Pieltain M., Castañón A., Flores M., Castañón J. (1996) Nutritive value of postharvest
 719 bean by-products (*Phaseolus vulgaris* L.) for ruminants. *Animal Feed Science and*
 720 *Technology* 62:271-275.

721 Prasad K., Khan A., Vellaikumar S., Devulapalli R., Ramakrishna Reddy C., Nigam S.,
 722 Blümmel M. (2010) Observations on livestock productivity in sheep fed exclusively
 723 on haulms from ten different genotypes of groundnut. *Animal Nutrition and Feed*
 724 *Technology* 10S:121-126. ISSN 0974-181X.
 725 <http://www.indianjournals.com/ijor.aspx?target=ijo...>

726 Quinlan R.J., Quinlan M.B., Dira S., Caudell M., Sooge A., Assoma A.A. (2015)
 727 Vulnerability and resilience of Sidama enset and maize farms in southwestern
 728 Ethiopia. *Journal of Ethnobiology* 35:314-336.

729 SAS. (2009) SAS/STAT ® 9.2 User's Guide, Second Edition. Cary, NC: SAS Institute Inc.
 730 <https://support.sas.com/documentation/cdl/en/statugintroduction/61750/PDF/default>
 731 [/statugintroduction.pdf](https://support.sas.com/documentation/cdl/en/statugintroduction/61750/PDF/default/statugintroduction.pdf).

732 Schiere J., Joshi A., Seetharam A., Oosting S., Goodchild A., Deinum B., Van Keulen H.
 733 (2004) Grain and straw for whole plant value: Implications for crop management
 734 and genetic improvement strategies. *Experimental Agriculture* 40:277-294.

735 Scully B., Wallace D. (1990) Variation in and relationship of biomass, growth rate, harvest
 736 index, and phenology to yield of common bean. *Journal of the American Society for*
 737 *Horticultural Science* 115:218-225.
 738 <http://journal.ashspublications.org/content/115/2/218.short>.

739 Sharma K., Pattanaik A., Anandan S., Blümmel M. (2010) Food-feed crops research: A
 740 synthesis. *Animal Nutrition and Feed Technology* 10S:1-10. ISSN : 0974-181X.

741 [http://www.indianjournals.com/ijor.aspx?target=ijor:anft&volume=10s&issue=spl&art](http://www.indianjournals.com/ijor.aspx?target=ijor:anft&volume=10s&issue=spl&article=001)
742 [icle=001](http://www.indianjournals.com/ijor.aspx?target=ijor:anft&volume=10s&issue=spl&article=001).

743 Shenk J.S., Westerhaus M.O. (1991a) Populations structuring of near infrared spectra and
744 modified partial least squares regression. *Crop Science* 31:1548-1555.

745 Shenk J.S., Westerhaus M.O. (1991b) Population definition, sample selection, and
746 calibration procedures for near infrared reflectance spectroscopy. *Crop Science*
747 31:469-474.

748 Singh B., Ajeigbe H., Tarawali S.A., Fernandez-Rivera S., Abubakar M. (2003) Improving
749 the production and utilization of cowpea as food and fodder. *Field Crops Research*
750 84:169-177.

751 Tadesse D., Alem T., Wossen T., Sintayehu A. (2014) Evaluation of Improved Varieties of
752 Haricot Bean in West Belessa, Northwest Ethiopia. *International Journal of Science*
753 *and Research (IJSR)* 3:2756-2759. ISSN (Online): 2319-7064.
754 <https://www.ijsr.net/archive/v3i12/U1VCMTU4MA==.pdf>.

755 Tar'an B., Michaels T.E., Pauls K.P. (2002) Genetic mapping of agronomic traits in
756 common bean. *Crop Science* 42:544-556.

757 Tolera A., Sundstøl F. (2000) Supplementation of graded levels of *Desmodium intortum*
758 hay to sheep feeding on maize stover harvested at three stages of maturity: 1. Feed
759 intake, digestibility and body weight change. *Animal Feed Science and Technology*
760 85:239-257.

761 Tullu A., Kusmenoglu I., McPhee K., Muehlbauer F. (2001) Characterization of core
762 collection of lentil germplasm for phenology, morphology, seed and straw yields.
763 *Genetic Resources and Crop Evolution* 48:143-152.

764 Van Soest P.J. (1994) *Nutritional ecology of the ruminant*. 2nd ed. Cornell University
765 Press, Ithaca, 476pp.
766 <http://www.cornellpress.cornell.edu/book/?GCOI=80140100037050>.

767 Van Soest P.v., Robertson J., Lewis B. (1991) Methods for dietary fiber, neutral detergent
 768 fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci
 769 74:3583-3597.

770 Williams P.C. (2001) Implementation of near-infrared technology, in: P. C. Williams, Norris,
 771 K.H. (Ed.), Near-infrared technology in the agricultural and food industries,
 772 American Association of Cereal Chemist St. Paul, Minnesota, USA. pp. 145–169.
 773 ISBN : 091325049X

774 Yoseph T., Gashaw G., Shiferaw W., Simon T., Mekonnen E. (2014) Evaluation of
 775 common bean [*Phaseolus vulgaris* (L.)] varieties for yield and yield components.
 776 Journal of Biology, Agriculture and Healthcare 4:22-25. ISSN 2225-093X (Online).
 777

778 **Table 1**

779 Trial sites description, genotypes tested and field operation for trials conducted at four
780 sites in 2013.

	<i>Shalla</i>	<i>Bako-Tibe</i> ⁴	<i>Boricha</i>	<i>Mandura</i>
GPS coordinates	7°281'N, 38°447'E	Comprised two sub-sites about 5 km apart at <i>Dambi Dima</i> , 9°110'N, 37°800'E and <i>Oda Haro</i> , 9°400'N, 37°190'E	6°947'N and 38°222'E	11°118'N and 36°722'E
Agro-ecology ¹	Semi-arid	Sub-humid	Sub-moist hot to warm lowland	Sub-humid hot to warm lowland
Soil type ²	Andosols	Alfisols	Eutric fluvisols	Red laterite
Mean annual rainfall (mm) ^{2,3}	773	1303	963	1942
Altitude (MASL)	1696	1692	1818	1477
Genotypes	A-Melka, Awash-1, Deme, Dimtu, Dinknesh, ECAB0056, ECAB0081, GLP2 and Nasir	Anger, Dimtu, Dinknesh, H-Dume, Ibado and Loko	A-Melka, Argene, Awash-1, Dimtu, Dinknesh, H-Dume, Ibado, Nasir and SARI	A-Melka, Argene, Awash-1, Dimtu, Dinknesh, H-Dume, Ibado, Nasir and SARI
Date of sowing	03 July	27 June	07 August	24 August
Date of harvesting	23 and 29 Oct	13 and 26 Oct	07 and 11 Nov	19 and 21 Nov

781 GPS, Geographic positioning system; MASL, Meters Above Sea Level;
782 Source, ¹ (Farrow, 2014) ² (Asfaw et al., 2013; Emiru, 2014; MARC, 2014; Negassa et al.,
783 2005); ³ Long term mean annual rainfall for the years 1978-2013, 1982-2014, 1996-2012
784 and 1987-2013 at *Shalla*, *Bako-Tibe*, *Boricha* and *Mandura* sites, respectively;
785 ⁴ The measurements at the two sub-sites (each 3 replications) were averaged and
786 considered as the *Bako-Tibe* site.

787
788
789
790

791 **Table 2**

792 Yields of seed and HPW, and HI, PUI and HPW morphological fractions of common bean
793 genotypes at *Shalla* (n = 3) and *Bako-Tibe* (n=3) in 2013.

Genotype	Yield (t/ha)				Morphological fractions (g/kg DM)		
	Seed	HPW	HI	PUI	Leaf	Stem	Pod wall
<i>Shalla</i>							
A-Melka	2.18 ^d	1.75 ^e	0.55 ^{ab}	0.79 ^c	64 ^d	692 ^b	243 ^c
Awash-1	2.05 ^d	1.59 ^e	0.56 ^a	0.81 ^{ab}	65 ^{cd}	688 ^b	247 ^c
Deme	2.83 ^{bc}	2.91 ^{bc}	0.49 ^{cd}	0.80 ^c	75 ^b	630 ^{cd}	295 ^b
Dimtu	2.53 ^{dc}	2.47 ^d	0.51 ^{cd}	0.76 ^d	48 ^e	733 ^a	220 ^d
Dinknesh	2.37 ^{dc}	2.30 ^d	0.51 ^{cd}	0.77 ^d	65 ^{cd}	689 ^b	245 ^c
ECAB0056	2.55 ^{dc}	2.83 ^c	0.47 ^d	0.77 ^d	65 ^{cd}	691 ^b	243 ^c
ECAB0081	3.13 ^{ab}	3.36 ^a	0.48 ^{cd}	0.82 ^a	84 ^a	614 ^c	302 ^{ab}
GLP2	2.52 ^{dc}	2.47 ^d	0.50 ^{cd}	0.81 ^{abc}	76 ^b	631 ^c	293 ^b
Nasir	3.47 ^a	3.19 ^{ab}	0.52 ^{bc}	0.79 ^c	70 ^c	620 ^c	310 ^a
Mean	2.62	2.54	0.51	0.79	68	665	266
Significance	0.0005	<0.0001	<0.004	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	11.3	7.5	4.7	1.2	4.3	1.4	2.9
<i>Bako-Tibe</i>							
Anger	0.74	0.60	0.55 ^{ab}	0.74	41 ^d	692 ^c	268 ^c
Dimtu	0.79	0.71	0.52 ^{abc}	0.74	38 ^e	712 ^b	250 ^d
Dinknesh	0.78	0.77	0.50 ^{bc}	0.74	45 ^c	674 ^d	281 ^b
H-Dume	0.93	0.95	0.49 ^c	0.77	77 ^a	635 ^e	288 ^a
Ibado	0.86	0.85	0.50 ^{bc}	0.71	46 ^c	710 ^b	243 ^d
Loko	0.67	0.52	0.57 ^a	0.76	68 ^b	726 ^a	206 ^e
Mean	0.79	0.74	0.52	0.75	52	692	256
Significance	0.892	0.367	0.030	0.079	<0.0001	<0.0001	<0.0001
CV (%)	34.8	33.6	4.8	3.0	2.4	0.6	1.6

794 Means with no superscript letters with a column of each trial site are not significantly different
795 (P>0.05).

796
797
798

799
800
801
802
803

Table 3

Yields of seed and HPW, and HI, PUI and HPW morphological fractions of common bean genotypes at *Boricha* (n=3), *Mandura* (n=3) and across both sites (n=6) in 2013.

Genotype	Yield (t/ha)		HI	PUI	Morphological fractions (g/kg DM)		
	Seed	HPW			Leaf	Stem	Pod wall
<i>Boricha</i>							
A-Melka	1.81	2.43 ^a	0.42	0.68	53 ^{ef}	734	213
Argene	1.28	1.98 ^{ab}	0.40	0.69	86 ^a	604	310
Awash-1	1.64	2.18 ^{ab}	0.44	0.70	77 ^{abc}	651	273
Dimtu	1.24	1.36 ^b	0.48	0.72	50 ^f	692	258
Dinknesh	2.09	2.55 ^a	0.44	0.71	78 ^{ab}	604	318
H-Dume	1.88	2.50 ^a	0.43	0.71	77 ^{ab}	598	324
Ibado	1.20	1.40 ^b	0.46	0.71	64 ^{de}	670	266
Nasir	2.03	2.59 ^a	0.44	0.71	65 ^{cde}	569	366
SARI	1.82	2.55 ^a	0.42	0.69	71 ^{bcd}	681	249
Mean	1.67	2.17	0.44	0.70	69	645	286
Significance	0.188	0.033	0.895	0.961	<0.0001	0.053	0.215
CV (%)	27.9	23.0	14.9	6.7	10.2	9.1	22.7
<i>Mandura</i>							
A-Melka	0.92 ^d	1.08 ^d	0.46 ^b	0.73	87 ^a	651 ^{ab}	263 ^c
Argene	0.46 ^e	0.59 ^e	0.44 ^b	0.72	84 ^{ab}	668 ^a	247 ^c
Awash-1	1.14 ^{cd}	1.20 ^d	0.49 ^a	0.74	81 ^b	626 ^{bcd}	293 ^b
Dimtu	1.59 ^b	1.96 ^{bc}	0.45 ^b	0.70	56 ^{ef}	637 ^{bc}	307 ^{ab}
Dinknesh	1.55 ^b	1.88 ^{bc}	0.45 ^b	0.70	53 ^f	642 ^{bc}	306 ^{ab}
H-Dume	1.88 ^a	2.29 ^a	0.45 ^b	0.71	54 ^{ef}	624 ^{cd}	322 ^a
Ibado	1.61 ^{ab}	2.07 ^{ab}	0.44 ^b	0.73	74 ^c	604 ^d	322 ^a
Nasir	1.35 ^{bc}	1.72 ^c	0.44 ^b	0.73	64 ^d	621 ^{cd}	316 ^{ab}
SARI	1.39 ^{bc}	1.75 ^{bc}	0.44 ^b	0.72	58 ^e	626 ^{bcd}	316 ^{ab}
Mean	1.32	1.61	0.45	0.72	68	633	299
Significance	<0.0001	<0.0001	0.0088	0.147	<0.0001	0.0038	0.0002
CV (%)	12.3	11.2	2.9	2.3	3.9	2.4	5.4
Environment							
<i>Boricha</i>	1.67 ^a	2.17 ^a	0.44	0.70	69	645	286
<i>Mandura</i>	1.32 ^b	1.61 ^b	0.45	0.72	68	633	299
Significance							
Genotype (G)	0.0006	0.0003	0.84	0.951	<0.0001	0.035	0.061
Environment (E)	0.0007	<0.0001	0.31	0.080	0.4727	0.357	0.361
G x E	0.011	<0.0001	0.83	0.761	<0.0001	0.042	0.257
LSD _{0.05}	0.40	0.45	0.06	0.04	6.0	53.0	59.0

Means with no superscript letters with a column of each trial site are not significantly different (P>0.05).

804
805
806

Table 4
Total N concentration, dry matter digestibility and fibre fractions (g/kg DM) of pod wall, haulm (stem+ little leaf) and HPW of common bean genotypes at *Shalla* (n=3) and *Bako-Tibe* (n=3) in 2013.

Genotype	Total N			DMD			aNDFom			ADFom		
	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW
<i>Shalla</i>												
A-Melka	7.5	6.8 ^{de}	7.0 ^{cd}	675 ^{bc}	489 ^{de}	535 ^{ef}	564 ^{cd}	749 ^{ab}	704 ^{ab}	416 ^b	591 ^a	548 ^{ab}
Awash-1	8.7	12.5 ^{ab}	11.6 ^a	624 ^e	554 ^c	571 ^{cd}	607 ^a	641 ^d	632 ^{de}	445 ^a	510 ^c	494 ^{de}
Deme	8.2	10.1 ^{bc}	9.6 ^b	696 ^{ab}	557 ^{bc}	598 ^{bc}	528 ^e	650 ^d	614 ^{ef}	380 ^c	508 ^c	470 ^e
Dimtu	6.2	6.1 ^e	6.1 ^d	657 ^{cd}	466 ^e	508 ^f	582 ^{bcd}	761 ^a	721 ^a	418 ^b	597 ^a	558 ^a
Dinknesh	10.3	8.9 ^{cd}	9.3 ^b	663 ^{cd}	485 ^e	529 ^{ef}	559 ^d	730 ^{ab}	688 ^{bc}	423 ^b	585 ^a	545 ^{ab}
ECAB0056	7.6	10.2 ^{bc}	9.5 ^b	635 ^{de}	533 ^c	558 ^{de}	585 ^{abc}	681 ^{cd}	657 ^{cd}	426 ^b	533 ^{bc}	507 ^{cd}
ECAB0081	8.2	14.4 ^a	12.5 ^a	705 ^a	622 ^a	647 ^a	521 ^e	575 ^e	559 ^g	383 ^c	456 ^d	434 ^f
GLP2	6.9	14.7 ^a	12.4 ^a	634 ^{de}	596 ^{ab}	607 ^b	587 ^{abc}	582 ^e	584 ^{fg}	409 ^b	447 ^d	436 ^f
Nasir	7.1	9.0 ^{cd}	8.4 ^{bc}	653 ^{cde}	530 ^{cd}	568 ^{cd}	603 ^{ab}	711 ^{bc}	677 ^{bc}	454 ^a	564 ^{ab}	529 ^{bc}
Mean	7.9	10.3	0.9.6	660	537	569	571	675	648	417	532	502
Significance	0.232	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	21.7	13.5	11.8	2.6	4.4	3.1	2.5	4.0	2.9	2.4	4.4	3.3
<i>Bako-Tibe</i>												
Anger	13.8 ^{ab}	12.9 ^{ab}	13.2 ^a	573 ^c	377 ^{bc}	429 ^{cd}	615 ^{ab}	723 ^b	694 ^{bc}	450 ^a	594 ^b	556 ^b
Dimtu	7.6 ^c	13.9 ^a	12.3 ^{ab}	606 ^b	415 ^b	463 ^{bc}	548 ^c	690 ^{bc}	654 ^{cd}	395 ^b	574 ^b	530 ^{bc}
Dinknesh	8.8 ^c	11.4 ^b	10.7 ^b	605 ^b	441 ^b	487 ^b	640 ^a	707 ^b	688 ^{bc}	468 ^a	570 ^b	541 ^b
H-Dume	7.3 ^c	12.0 ^{ab}	10.7 ^b	610 ^b	524 ^a	549 ^a	644 ^a	640 ^c	641 ^d	469 ^a	506 ^c	495 ^c
Ibado	10.8 ^{bc}	7.8 ^c	8.6 ^c	629 ^b	349 ^c	417 ^d	607 ^b	782 ^a	739 ^a	449 ^a	654 ^a	604 ^a
Loko	16.2 ^a	12.5 ^{ab}	13.2 ^a	674 ^a	398 ^{bc}	455 ^{bcd}	549 ^c	744 ^{ab}	704 ^{ab}	411 ^b	598 ^b	560 ^b
Mean	10.8	11.8	11.4	616	417	467	600	714	687	440	583	548
Significance	0.002	0.001	0.002	0.0001	0.0012	0.0006	<0.0001	0.0025	0.0039	0.005	0.0014	0.0013
CV (%)	21.2	10.4	10.2	2.5	8.7	5.5	3.1	4.4	3.5	4.9	5.0	3.9

Means with no superscript letters with a column of each trial site are not significantly different (P>0.05).

813
814
815

Table 5

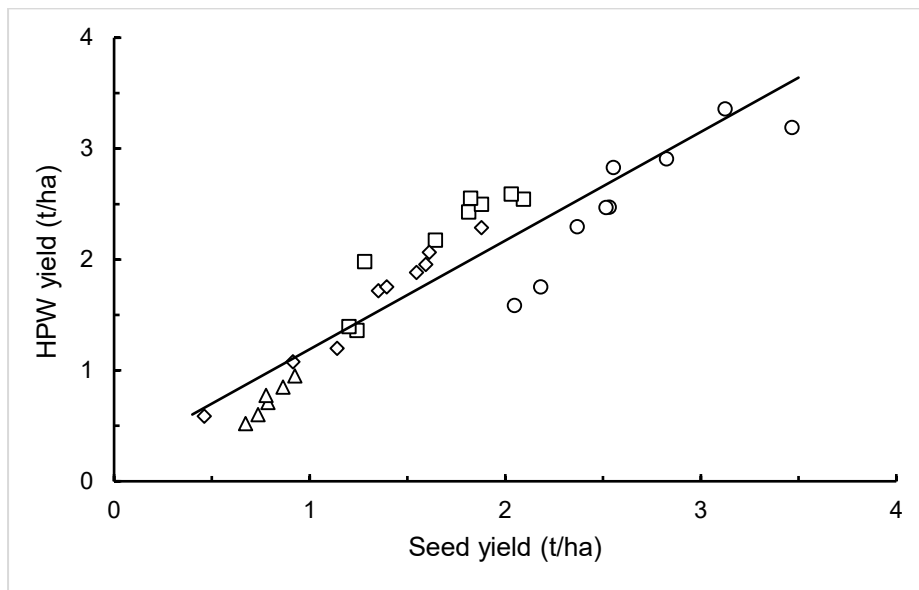
Total N concentration, dry matter digestibility and fibre fractions (g/kg DM) of pod wall, haulm (leaf +stem) and HPW of common bean genotypes at *Boricha* (n=3), *Mandura* (n=3) and averaged across both sites (n=6) in 2013.

Genotype	Total N			DMD			aNDFom			ADFom		
	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW	Pod wall	Haulm	HPW
<i>Boricha</i>												
A-Melka	8.6 ^{bcd}	7.5	7.8	612	401	446	618	801	762	476 ^{ab}	650 ^a	614
Argene	11.7 ^a	7.5	8.9	635	411	481	597	789	728	453 ^{bc}	634 ^{ab}	577
Awash-1	10.0 ^{abc}	7.8	8.4	622	412	469	608	772	727	464 ^{ab}	613 ^c	573
Dimtu	6.6 ^d	7.0	6.9	606	410	460	623	791	748	470 ^{ab}	633 ^{ab}	591
Dinknesh	7.7 ^d	7.0	7.2	617	420	482	622	790	737	485 ^a	636 ^{ab}	589
H-Dume	10.5 ^{ab}	6.9	8.1	631	415	485	605	785	727	475 ^{ab}	627 ^{bc}	578
Ibado	7.5 ^d	6.7	6.9	622	412	467	603	795	745	436 ^c	620 ^{bc}	571
Nasir	8.2 ^{cd}	6.2	6.9	619	405	483	621	790	728	484 ^a	633 ^{ab}	579
SARI	8.1 ^{cd}	8.1	8.1	614	407	458	615	788	745	476 ^{ab}	634 ^{ab}	595
Mean	8.8	7.2	7.7	620	410	470	612	789	739	469	631	585
Significance	0.0015	0.1644	0.0972	0.1253	0.863	0.3435	0.2803	0.2925	0.2809	0.0104	0.0342	0.1283
CV (%)	13.6	11.0	11.6	1.8	3.5	4.5	2.3	1.5	2.5	3.0	1.7	2.9
<i>Mandura</i>												
A-Melka	10.0 ^b	9.3	9.5	646 ^a	436	491	573 ^e	750	703	435 ^e	597	554
Argene	11.7 ^a	10.9	11.1	640 ^{ab}	452	499	577 ^{de}	712	679	436 ^e	558	528
Awash-1	9.2 ^{bc}	8.9	9.0	612 ^e	438	489	612 ^b	747	707	463 ^b	598	558
Dimtu	9.6 ^b	8.0	8.4	616 ^{cde}	395	463	596 ^{bcd}	761	710	441 ^{cde}	610	558
Dinknesh	9.5 ^{bc}	8.0	8.5	623 ^{cd}	384	457	589 ^{cde}	775	718	435 ^e	624	566
H-Dume	7.1 ^d	6.1	6.4	606 ^e	398	465	634 ^a	798	745	481 ^a	631	582
Ibado	6.9 ^d	8.9	8.2	628 ^{bc}	468	520	608 ^{bc}	750	704	439 ^{de}	596	545
Nasir	7.9 ^{cd}	8.9	8.6	623 ^{cd}	458	510	604 ^{bc}	739	696	455 ^{bc}	587	545
SARI	8.4 ^{bcd}	6.7	7.2	613 ^{cde}	439	494	603 ^{bc}	769	71.6	453 ^{bcd}	617	565
Mean	8.9	8.4	8.5	623	430	488	600	756	709	449	602	556
Significance	0.0002	0.3671	0.1722	0.0005	0.0853	0.0608	0.0002	0.4655	0.4432	<.0001	0.2815	0.2894
CV (%)	10.4	27.4	20.7	1.4	8.2	4.9	1.9	5.5	4.3	2.0	5.4	4.2
Environment												
<i>Boricha</i>	8.8	7.2 ^b	7.7 ^b	620	410 ^b	470 ^b	612 ^a	789 ^a	739 ^a	469 ^a	631 ^a	585 ^a
<i>Mandura</i>	8.9	8.4 ^a	8.5 ^a	623	430 ^a	488 ^a	600 ^b	756 ^b	709 ^b	449 ^b	602 ^b	556 ^b
Significance												
Genotype (G)	<0.0001	0.336	0.024	0.025	0.326	0.22	0.003	0.515	0.378	0.0003	0.262	0.133
Environment (E)	0.492	0.019	0.017	0.324	0.029	0.02	0.0005	0.001	0.0003	<0.0001	0.0004	<0.0001
G x E	<0.0001	0.344	0.161	0.033	0.132	0.12	0.0006	4501	0.327	0.004	0.2300	0.323
LSD _{0.05}	0.85	2.10	1.47	13.89	36.52	29.09	13.34	37.99	29.66	.4.02	29.85	24.58

Means with no superscript letters with a column of each trial site are not significantly different (P>0.05).

816
817

818



819

820 **Figure 1.** Relationship between the haulm + pod wall (HPW) yield (t/ha) (Y) and
 821 seed yield (t/ha) (X) in common bean genotypes at *Shalla* (o), *Bako-Tibe* (Δ),
 822 *Boricha* (\square) and *Mandura* (\diamond) in 2013.

823 *The regression relationships for each of the four trial sites and pooled data were:*

824 *Shalla.* $Y = 1.23X - 0.68$ ($r=0.91$; $P<0.001$; $n=9$);

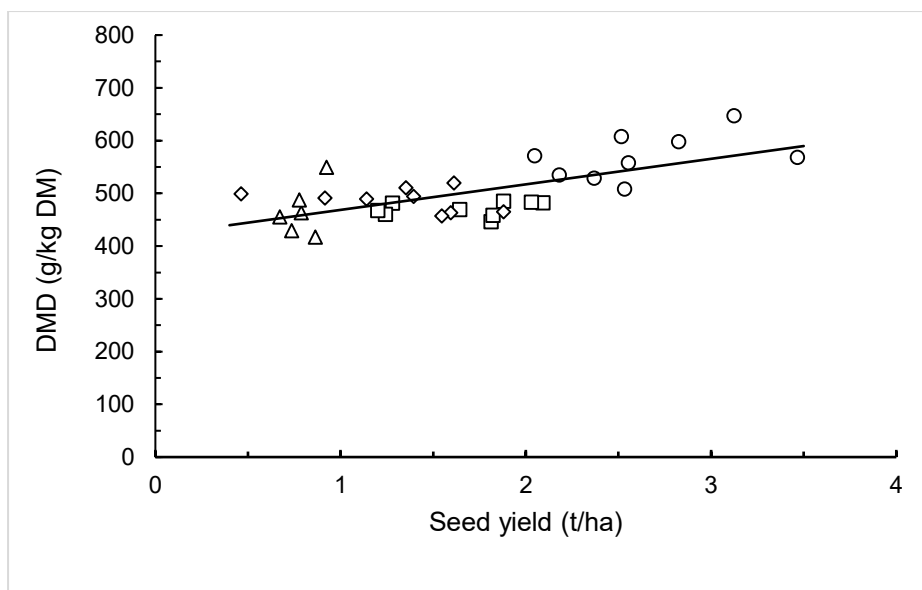
825 *Bako-Tibe.* $Y = 1.72X - 0.63$ ($r=0.98$; $P<0.001$; $n=6$);

826 *Boricha.* $Y = 1.32X - 0.03$ ($r=0.93$; $P<0.001$; $n=9$);

827 *Mandura.* $Y = 1.26X - 0.06$ ($r=0.99$; $P<0.0001$; $n=9$);

828 *Pooled relationship:* $Y = 0.98X + 0.21$ ($r=0.92$; $P<0.0001$; $n=33$).

829



830

831 **Figure 2.** Relationship between the haulm + pod wall (HPW) DMD (g/kg DM) (Y) and
 832 seed yield (t/ha) (X) in common bean genotypes at *Shalla* (o), *Bako-Tibe* (Δ),
 833 *Boricha* (\square) and *Mandura* (\diamond) in 2013.

834 *The regression relationships for each of the four trial sites and pooled data were:*

835 *Shalla. $Y = 43.62X + 454.52$ ($r = 0.45$; $P=0.221$; $n=9$);*

836 *Bako-Tibe. $Y = 262.14X + 258.50$ ($r = 0.50$; $P=0.317$; $n=6$);*

837 *Boricha. $Y = 9.36X + 454.77$ ($r = .0.24$; $P=0.538$; $n=9$);*

838 *Mandura. $Y = -18.59X + 512.20$ ($r = -0.37$; $P=0.332$; $n=9$);*

839 *Pooled relationship: $Y = 48.40X + 420.21$ ($r = 0.68$; $P<0.0001$; $n=33$).*

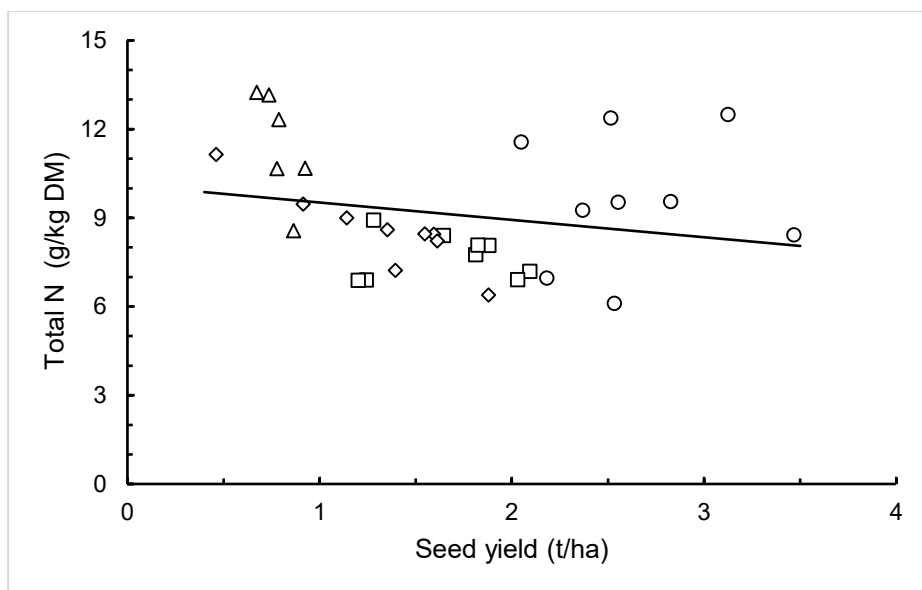


Figure 3. Relationship between the haulm + pod wall (HPW) N (g/kg DM)concentration (Y) and seed yield (t/ha) (X) in common bean genotypes at *Shalla* (o), *Bako-Tibe* (Δ), *Boricha* (\square) and *Mandura* (\diamond) in 2013.

The regression relationships for each of the four trial sites and pooled data were:

Shalla. $Y = 0.37X + 8.63$ ($r = 0.07$; $P=0.852$; $n=9$);

Bako-Tibe. $Y = -15.18X + 23.50$ ($r = -0.75$; $P=0.085$; $n=6$);

Boricha. $Y = -0.13X + 7.90$ ($r = -0.06$; $P=0.878$; $n=9$);

Mandura. $Y = -2.82X + 12.27$ ($r = -0.90$; $P<0.001$; $n=9$);

Pooled relationship: $Y = -0.59X + 10.11$ ($r = -0.22$; $P=0.22$; $n=33$).